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LCA FOR AGRICULTURE

System delimitation in agricultural consequential LCA

Outline of methodology and illustrative case study of wheat in Denmark

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Abstract

Background, aim, and scope When dealing with system delimitation in environmental life cycle assessment (LCA), two methodologies are typically referred to: consequential LCA and attributional LCA. The consequential approach uses marginal data and avoids co-product allocation by system expansion. The attributional approach uses average or supplier-specific data and treats co-product allocation by applying allocation factors. Agricultural LCAs typically regard local production as affected and they only include the interventions related to the harvested area. However, as changes in demand and production may affect foreign production, yields and the displacement of other crops in regions where the agricultural area is constrained, there is a need for incorporating the actual affected processes in agricultural consequential LCA. This paper presents a framework for defining system boundaries in consequential agricultural LCA. The framework is applied to an illustrative case study; LCA of increased demand for wheat in Denmark. The aim of the LCA screening is to facilitate the application of the proposed methodology. A secondary aim of the LCA screening is to illustrate that there are different ways to meet increased demand for agricultural products and that the environmental impact from these different ways vary significantly.

Materials and methods The proposed framework mainly builds on the work of Ekvall T, Weidema BP (*Int J Life Cycle Assess* 9(3):pp. 161–171, 2004), agricultural statistics (FAOSTAT, *FAOSTAT Agriculture Data*, Food and Agriculture Organisation of the United Nations (2006), http://apps.fao.org/ (accessed June)), and agricultural outlook (FAPRI, *US and world agricultural outlook*, Food and Agriculture Research Institute, Iowa, 2006a). The framework and accompanying guidelines concern the suppliers affected, the achievement of increased production (area or yield), and the substitutions between crops. The framework, which is presented as a decision tree, proposes four possible systems that may be affected as a result of the increased demand of a certain crop in a certain area.

Results The core of the proposed methodology is a decision tree, which guides the identification of affected processes in consequential agricultural LCA. The application of the methodology is illustrated with a case study presenting an LCA screening of wheat in Denmark. Different scenarios of how increased demand for wheat can be met show significant differences in emission levels as well as land use.

Discussion The great differences in potential environmental impacts of the analysed results underpin the importance of system delimitation. The consequential approach is appointed as providing a more complete and accurate but also less precise result, while the attributional approach provides a more precise result but with inherent blind spots, i.e. a less accurate result.

Conclusions The main features of the proposed framework and case study are: (1) an identification of significant sensitivity on results of system delimitation, and (2) a formalised way of identifying blind spots in attributional agricultural LCAs.

Recommendations and perspectives It is recommended to include considerations on the basis of the framework presented in agricultural LCAs if relevant. This may be

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done either by full quantification or as qualitative identification of the most likely ways the agricultural product system will respond on changed demand. Hereby, it will be possible to make reservations to the conclusions drawn on the basis of an attributional LCA.

Keywords Agriculture · Consequential modelling · Marginal data · System boundaries · System delimitation · System expansion · Wheat

1 Background, aim, and scope

When dealing with system delimitation in environmental life cycle assessment (LCA), two approaches are often referred to: consequential LCA and attributional LCA. The attributional LCA, which is also referred to as traditional and retrospective LCA, uses average or supplier-specific data and treats co-production by applying allocation factors (Ekvall et al. 2005). On the other hand, consequential LCA, which is also referred to as prospective LCA, applies marginal data and treats co-production by system expansion. Marginal data represents the supplier or technology that is actually affected by a change in demand. Attributional LCAs of agricultural products mainly deal with the environmental interventions related to the harvested area only.

However, it may be questioned if that kind of approach provides sufficient decision support. LCAs may be used as decision support or as a way to better understand the magnitude and origins of environmental impacts. A relevant focus of an LCA should be to assess the consequences of a change compared to the present situation. Hence, LCA may have a role to play in environmental reform, i.e. it is used for exploring roads to environmentally sound ways of producing, consuming, regulating and living. When using LCAs for this purpose, actual affected processes, suppliers and technologies should be taken into account rather than weighted-out averages of all technologies. Ekvall and Weidema (2004) provide guidelines for identifying such marginal technologies in consequential LCA. Consequential LCAs of agricultural products have been conducted, e.g. Dalgaard et al. (2008), Nielsen et al. (2005), Weidema et al. (2005) and Cederberg and Stadig (2003).

The consequential modelling in the agricultural stage in Dalgaard et al. (2008), Nielsen et al. (2005) and Weidema et al. (2005) comprises consideration of the marginal sources of energy and protein fodder, fertiliser and electricity. In addition, Nielsen et al. (2005) have identified the marginal suppliers of various crops in terms of farm types. The marginal suppliers are represented as a weighted range of farm types, which are identified through economic modelling of the responses to changes in demand for different agricultural products. Cederberg and Stadig (2003) consider system expansion to avoid co-product allocation between milk and beef. The considered systems are conventional combined milk and meat production, alternative meat production (suckler cows), and surplus calves.

However, none of these studies take into account the actual marginal effects of increasing production of a certain crop in a certain area, i.e. increase in production of one crop may take place at the expense of production of other crops in the region, by increased yield or by expansion of the total cultivated land. Weidema (2003) has identified the marginal crop in the EU and has thereby partly incorporated the actual affected technology (area or yield), regions and crops. Still, so far no agricultural LCAs have been identified that adopt consequential modelling of change in demand for crops. In many regions, the area available for agricultural cultivation is constrained, e.g. in Europe where the cultivated acreages have declined during the last decades (FAOSTAT 2006). If production of wheat increases in Denmark, for example, it is not likely that either the agricultural area will expand or the yield increase. Instead, the cultivation of other crops will decrease. This decrease in supply of other crops will be likely to be compensated for by increases in cultivation of the crop or substitutable crops in other parts of the world.

A consequential approach in accordance with the cause-effect relations described above has been applied to LCA studies within other areas than agriculture, e.g. building insulation (Schmidt et al. 2004). In Schmidt et al. (2004), different material options for building insulation are compared. Among others, the insulation from paper waste is included. When using waste paper for production of insulation materials, less paper waste will be available for paper recycling. Thus, in relation to the maintenance of paper supply, the production of virgin paper is regarded as affected. Despite the fact that such consequential system delimitation has not yet found its way into agricultural LCAs, similar approaches are common practice in foresights and agricultural outlooks, e.g. FAO (2003a) and FAPRI (2006a). This article investigates how such system expansions after the cause–effects chain can be taken into account in LCA. Furthermore, it analyses the implications of this approach for the inventory and presents an example of the effects on the result in the life cycle impact assessment (LCIA) phase.

In the first part, this article draws a methodological framework with which system expansion between crops and regions can be analysed. The second part provides an illustrative example in which the methodological framework is applied to different scenarios for how increased demand for wheat in Denmark can be met.

2 Materials and methods

2.1 Consequential system delimitation for agricultural LCA

The consequential approach has been applied to system delimitation in the framework proposed in this article. The attributional approach to system delimitation takes its point of departure in physical flows, while the consequential approach focuses on causal relations within the market (Weidema 2003; Ekvall and Weidema 2004). The consequential approach implies that marginal, i.e. actual affected processes are included and that co-product allocation is avoided by system expansion. The main argument for applying the consequential approach is the fact that only the actual affected processes are included (Weidema 2003). Technologies that are not likely to respond to a change in demand should not be included in an LCA, as this would not reflect the actual change in environmental impact.

Increase in the demand for a certain crop in a certain region can principally be met by affecting one or a combination of the four different systems described in the following. The two first systems imply increased production in the region where the crop is demanded. System 1 involves changes in agricultural production in the region where the crop is demanded. This may be done either by increased productivity per unit of area (e.g. fertiliser, irrigation, pesticides, seed improvements, agricultural practice) or by transformation of non-cultivated land (nature) into agricultural land. In system 2, the change in the cultivated area of the desired crop affects the area cultivated with other crops and imbalances are regulated by foreign trade. In system 3, the desired increased demand is not compensated for in either the local region or by suppliers in other parts of the world. Thus, the affected system is a change in the net global production of crops. In system 4, the increased demand in a certain area is met by increased import.

If system 2 is affected, the marginal supplier of the displaced crops should be identified and the marginal supplier of that crop should be identified. If system 3 is affected, there will be a net change in the supply of the marginal crop. The effects are related to the marginal consumers of the marginal crop. The effects are associated either with the products they buy instead or with a general change in food security if prices change. Such effects are seldom included in LCAs because the impacts are very complex to identify or they are of social character. Social impacts fall out of the common scope of LCA (Finkbeiner et al. 2006), but the activity in this area is increasing (Dreyer et al. 2006). However, this article does not attempt to investigate this aspect further.

In the following, the general implications for the system inventoried will be outlined for an increase in demand of a certain crop *X* in a certain region A. This is shown in Fig. 1. The implications are investigated for a stand-alone increase in demand, i.e. assuming no trade-offs. If more carrots are consumed, for instance, this is investigated without looking at the simultaneous decrease in the consumption of tomatoes, for example. When applied in a specific LCA, two such stand-alone investigations are typically combined to study a trade-off, e.g. between substitutable amounts of carrots and tomatoes. The description takes its point of departure in how the four different systems mentioned may be affected. In section 3, the method outlined in this section is applied to an empirical study on increased demand for wheat in the EU.

When the method in Fig. 1 is to be used, it is important to be aware of the time frame, the geographical delimitation of the market (local, regional or global) and to define which crops are substitutable. In general, the proposed method is valid for short to mid-term changes, i.e. a few years to approximately 10 years. For changes that reach more than 10 years out in the future, the marginal suppliers may change and new cultivation techniques/practices may be introduced affecting the yields significantly. In addition, as the marginal suppliers are identified using agricultural outlooks reaching 10 years ahead, a longer time frame would require changes in the use of data. It is important to determine the geographical delimitation because it defines the market on which the marginal supplier is to be identified.

Examples of global markets are the markets for cereals and protein and oil crops. An example of a regional market is the market for sugar in the EU. Tariffs on imported sugar make the locally produced sugar more competitive. However, if the purpose of the LCA is to assess tariff regulations, the market is global. The identification of substitutable crops is important because it may determine which crop substitutions will take place. Not much information exists on that. However, as a default assumption, substitutions are only expected to occur within the same crops or derived products, e.g. wheat substitutes wheat and vegetable oil from oil crops substitutes vegetable oil.

The method in Fig. 1 implies two major simplifications of reality. First, the outcomes of boxes with questions 1), 2), 6) and 9) are shown as discrete values, i.e. either yes or no. However, these discrete outcomes are more likely to be represented as real values distributing a share to yes as well as no. This means that the resulting affected system may be a combination of the four systems shown. Section 3 provides an example of this in which a scenario for the combination of systems is conducted (scenario 6).

Second, the figure presumes that only one crop and one region is marginal. In reality, it is more likely that a range of crops will be marginally affected when the area of agricultural land is changed. Also more than one supplier

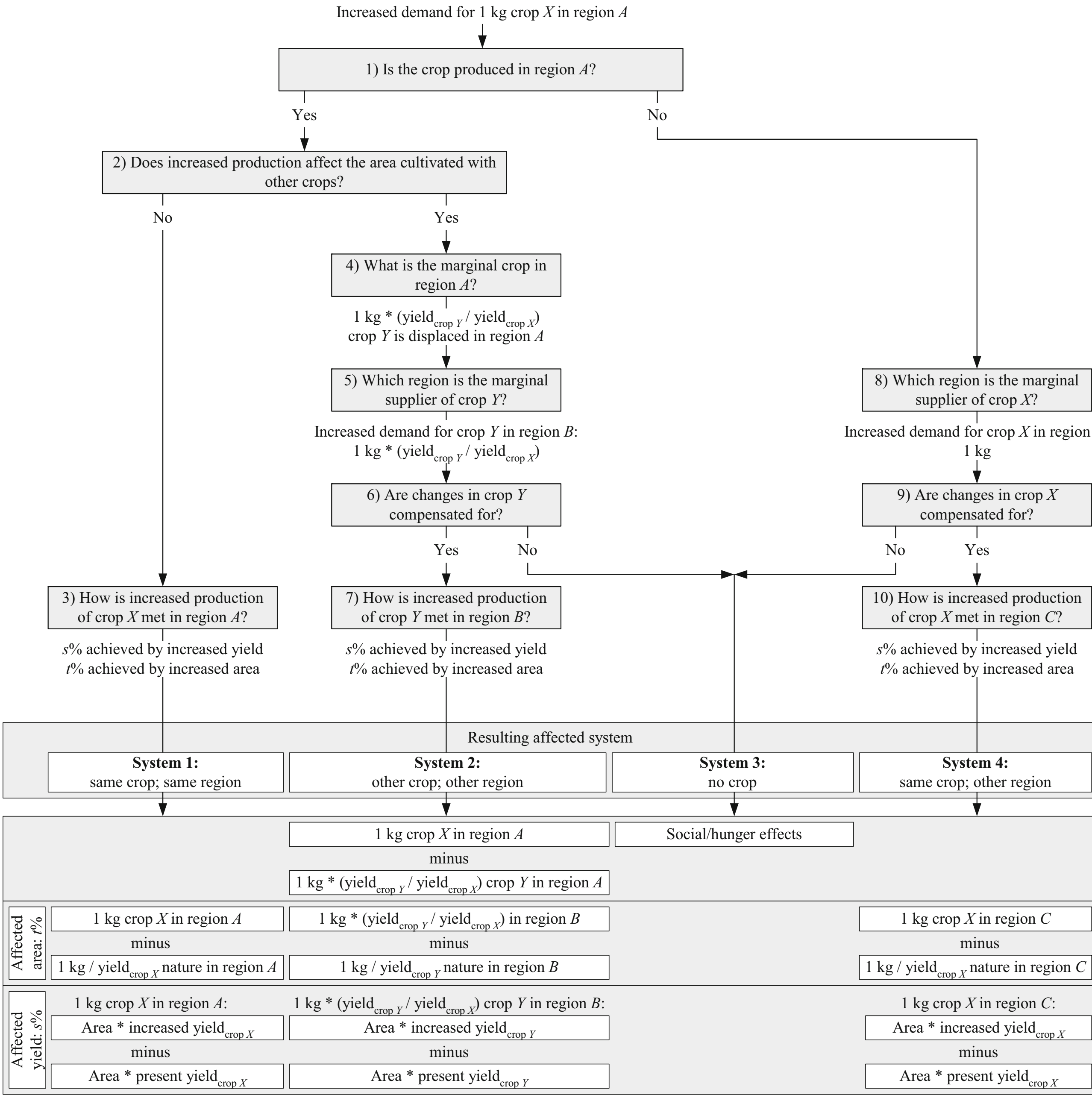

Fig. 1 Decision tree for determination of which processes are affected due to an increase in production of 1 kg of crop *X* in region *A*. Unit for yield in the figure is kg/m^2y

will probably respond to changes. One example of an LCA applying a range of different processes as the marginal has been identified: Nielsen et al. (2005) apply weighed-out shares of different farm types as affected when production of a certain crop is considered. The range of marginal affected farm types in Nielsen et al. (2005) is determined from an economic model described in Dejgård et al. (2001). However, this article does not investigate this aspect further.

A possible critique of the methodology presented in the figure is that a never-ending loop running through questions 2 and 7 is in principle possible. In the real world such ripple effects will probably occur. However, as questions 4 and 5 identify the marginal crop and its marginal supplier, and as the factor of crop displacements will decrease for each loop, the inherent assumption in the model to only include one loop is regarded as a good proxy for the actual displacements that are taking place. The four potentially affected systems are further described in the following.

System 1 When the production of a crop is increased in a certain region it is relevant to find out if this

increase will affect the overall agricultural area and/or the yield of the crop in the region (question 2 in Fig. 1). If this is the case, no other crops in the region are affected and the increase may be met by increased yield, increased area or a combination (question 3 in the figure). The increased demand is then met by the resulting affected system, which consists of a share t% representing changes in the cultivated area and a share s% representing changes in the yield. Interventions related to changes in the cultivated area are the emissions from the cultivated area minus the interventions from the transformed land (nature). Interventions related to increased yield are determined by the difference of a given area with higher yields minus a corresponding area with status quo yield. This is further described in Section 2.3.

System 2 In the case when neither the total cultivated area in region *A* nor the yield of crop *X* in region *A* are likely to increase, the increased production may take place at the expense of other crops in region *A*. This (or these) crop(s) is(are) the marginal crop(s), i.e. the one that is most likely to be affected in region *A* (question 4 in the figure). The procedure for identifying marginal suppliers is described in Weidema (2003). The amount of the displaced crop *Y* is determined by the ratio between annual yields of crops *Y* and *X* in region *A*. Question 5 identifies the marginal supplier, region B, of the displaced crop *Y*. The outcome of question 6 determines whether decreased production of a certain crop *Y* in a certain region *A* will be compensated for or not. Compensation, if it takes place, will most likely take place in the region B identified as the marginal supplier of crop *Y*. Then, corresponding to question 3, the way of increasing production of crop *Y* in region *B* should be determined in terms of increased converted area (*t*%) and increased yield (*s*%). The resulting affected system includes: production of 1 kg crop *X* in region *A*. As crop *X* displaces cultivation of other crops, the correspondingly displaced production of crop *Y* in region *A* is subtracted. The decrease in production of crop *Y* in region *A* is then compensated for by increased production in another region, *B*. The interventions in region *B* are determined corresponding to region *A* in system 1.

System 3 If no compensation for the decrease in the cultivation of crop *X* or *Y* takes place, the resulting system will be a decreased supply to the global market of crop *X* or *Y*. This is likely to decrease the availability of the crop and to increase world market prices, which again may affect the poorest costumer for this specific crop. According to FAO (2003a), reductions of cereal production in the OECD countries would be compensated for by factors of only 23% for maize and 30% for wheat by increased production in developing countries. This underpins the fact that system 3 is actually likely to be affected by changes in demand.

System 4 This system represents the situation when increased demand is met by increased import. System 4 is likely to be the case of regions with non-regulated constrained agricultural production, e.g. if the EU starts to demand more biodiesel based on vegetable oils without any initiatives encouraging increased local production.

2.2 What are marginal changes; increased yield or transformation of land?

The identification of how increased demand for the considered crop is met, i.e. percentages *s* and *t* in Fig. 1, can be done either by applying statistic material (e.g. FAOSTAT 2006) or agricultural outlook (e.g. FAPRI 2006a). This means that the applied increases in area and yield are presumed to be entirely caused by the increased demand for the desired crop. However, as many other driving forces for increasing yields and developing new agricultural land exist, the actual explanatory relation between increased demand and increased area and yield may be somewhere between 0 and 100%. Examples of driving forces of increasing yields are food security (Wiebe 2003), poverty reduction (FAO 2005, p 75), subsidies based on production as in the EU before the reform of the CAP[1] enacted in 2003 (European Commission 2006), land consuming activities such as urbanisation and conservation of nature, which cause less available land for agriculture (Wiebe 2003), and corresponding to the previous; the lack of available land, which causes increased competition of land (Lindeijer et al. 2002), which again leads to increased land prices and economic incentives for increasing yields.

Examples of driving forces for developing new agricultural land are available land and economic incentives for farmers[2] combined with a structural framework that allows

[0] CAP—Common Agricultural Policy. After the reform of the CAP in 2003, subsidies are no longer given per volume of agricultural production (European Commission 2006)

[0] According to WWF (2006), deforestation rates in Brazil Amazonas have declined by 30% in 2004/2005 due to falling prices for soy beans

conversion to occur (regulation and infrastructure); increased demand due to increased population (Cropper and Griffiths 1994), and migration programmes as in Indonesia, also caused by increased population (Sunderlin and Resosudarmo 1999). As can be seen in the above, deforestation/land transformation is driven by a complex combination of different levels of causes composed by actors, immediate causes and underlying causes forming a cause–effect chain (ProForest 2003).

Not all of the above-mentioned factors will be present in a cause–effect chain from a specific increased demand to increased area and yield. Therefore, some improvements of yield and conversion of non-cultivated land into agricultural land may be assumed to take place regardless of changes in market demand. However, it is very difficult to determine the amount of demand-driven changes in areas and yields and those that are endogenous. Therefore, the model introduces the assumption that the proportion between changes in yield and changes in cultivated area is the same for demand-driven and endogenous changes. By doing so, a change in production can easily be distributed to changes in yield and changes in area by looking into historical agricultural statistics or predicted developments in agricultural outlooks. FAPRI (2006a), for example, provides predictions for agricultural production the next decade with which annual increases in area and yield for several crops in most regions in the world can be determined.

2.3 How to model increased yield?

If the percentage s in Fig. 1 is >0 then a share of the increase in the desired crop is met by increased yield. The main challenge here is to determine how increased yield is achieved. FAO (2003b) points at the following agricultural inputs when it comes to important factors that influence the productivity of agriculture: irrigation, fertiliser and agricultural machinery. Besides these traditional means, the following may also help increasing yields: weed control (often pesticides), shifting to GMO, double-cropping (more than one crop-rotation per year) and better management (e.g. variety selection, seed improvement, scheduling and timing of fertiliser, pesticide, drainage and irrigation). This determination may rely on specific considerations for the particular region. In countries with low input of fertiliser, an easy way of increasing yields is by adding more fertiliser, while less effect can be achieved for regions with higher fertiliser inputs (Dobermann 2005). If increase in yields is assumed to be achieved by additional application of fertiliser, the additional amount of fertiliser needed can be estimated from Table 1 presented below. It is stressed that Table 1 is based on fertiliser/yield graphs from different sources and that the given numbers are attended with some uncertainty due to the reading of the slopes of graphs.

It appears from Table 1 that the modelling of increased yield is extremely sensitive to the choice of reference fertiliser application (varies within up to a factor of 14 for maize in Nebraska), and great differences from source to source on the same crops are also present (varies within up to a factor of 2.8 for winter wheat). When determining the reference fertiliser application, three opportunities exist: (1) the reference is represented by the average fertiliser application on the relevant crop in the relevant country/region, (2) the reference application is below the average, or (3) the reference application is above the average. On one hand, from an economic point of view, the largest economic return is achieved by applying more fertiliser where it has the largest effect, i.e. applying the fertiliser on soils with a present low fertiliser input. On the other hand, it is often the well-established and well-managed farms that will optimise yields, i.e. applying more fertiliser on soils, which already achieve a high input of fertiliser. If no information is available about the soils which will achieve additional fertiliser, the regional average can be applied as a default.

Table 1 Yield responses to additional fertiliser input for different crops at different levels of fertilising

Crop and region	Δyield (kg/ha)/ΔN-rate (kg N/ha)			
	0–50 kg N/ha	50–100 kg N/ha	100–150 kg N/ha	150–200 kg N/ha
Maize (Nebraska, USA)(1)	56	19	7	4
Maize (Oklahoma, USA) (2)	24	22	12	8
Winter wheat (Oklahoma, USA) (2)	15	6	–	–
Winter wheat (Sweden) (3)	40	17	12	4
Rapeseed (Denmark) (4)	13	15	9	4
Rapeseed (Germany) (5)	10	12	10	4
Soy (Argentina) (6)	0	0	0	0
Fresh fruit bunches from oil palm (Malaysia) (7)	149	87	62	48

(1) Dobermann (2005), (2) Johnson and Raun (2003), (3) Delin et al. (2005), (4) Pedersen (2005), (5) Rathke et al. (2006), (6) No N-fertiliser is applied in soy cultivation, because it is a legumes crop (Dalgaard et al. 2008). Thus, no response to additional N-fertiliser input is expected. (7) Corley and Tinker (2003)

This section has only described how to model increased yield in terms of additional N-fertiliser input. When modelling increased yield, other means should also be considered—especially in areas where fertiliser is constrained, e.g. in many areas of the EU, where the permitted fertiliser input is to a broad extent determined by the Water frame directive (European Council 2000) and the Nitrate directive (European Council 1991) or in soy cultivation, which may not respond to additional N-fertiliser input.

2.4 Resulting system may be a combination of several systems

Questions 1, 2, 6 and 9 in Fig. 1 may not always be answered satisfactorily by either yes or no, i.e. more than one system should be considered as affected. The shares of systems affected then have to be determined. For question 1, this section describes how to use price elasticities[3] of demand and supply in estimating market response to a change in demand of a certain commodity. Price elasticities may not help answering question 2 as this is determined among others by specific land regulation, the land available for transformation, agricultural regulation, research and innovation for increasing yields, and prices for increasing production in region *A* compared to prices for import from region *B*. Therefore, the shares of yes and no in question 2 should be estimated by use of specific considerations on the above-mentioned influential factors.

Theoretically, price elasticities can be used for answering questions 6 and 9, but then changes in all regions of the world should be considered rather than only the changes in the region, which is most likely to respond. The reason for this is the fact that the marginal suppliers are much more likely to respond to a change in demand than the average world market. If the marginal supplier was the only supplier affected, then a change in demand at 1 kg crop, would result in an increase of >1 kg. In normal LCAs, it would be too complex to model responses in all regions in the world. Therefore, more generalised measures can be applied until models allowing model responses in all regions of the world are available, the generalised measures presented here could serve as first estimates.

Question 1 Regarding price elasticities, the common applied default assumption in LCA is that neither supply nor demand affects prices, and that prices are determined by the long-term marginal production costs (Weidema 2003, p. 37). The implication of this is that demand for one unit of a product leads to an additional supply of one unit product. Correspondingly, the supply of one unit product as a dependant co-product commonly leads to the substitution of one unit of a substitutable product. However, part of this common approach has been criticised in, among others, Guinée et al. (2002, p. 514–515) and Ekvall and Weidema (2004) who suggest the application of elasticities as a more realistic approach. Guinée et al. (2002) argue that co-production allocation using prices as an allocation factor should be applied, as the lack of data on price elasticities causes an application of assumptions, which are too simplifying.

Relating to question 1 in Fig. 1, the increased demand of rapeseed in Europe, for example, may simultaneously cause an increased rapeseed production in the EU (answer = yes to question 1) and an increased production abroad for export to the EU (answer = no to question 1). The ratio between yes and no can be estimated by using the likeliness of the EU's agriculture to respond to a changed demand, ΔD = the entry in Fig. 1; 1 kg crop *X* in region *A*. When applying common formulas on price elasticities on demand and supply (Madsen et al. 1988) and assuming that supply equals demand (which is the case for perfect markets in the long term), the following ratio between changes in demand (ΔD) and supply (ΔS) can be established by Eq. (1).

$$\Delta S = \Delta D \frac{\eta_S}{\eta_D} \tag{1}$$

where

η_S and η_D denote price elasticities on supply and demand, respectively.

Values for the most important crops in most regions of the world can be found in FAPRI (2006b).

Thus, Eq. 1 can be used for determining how European agriculture responds to an increase in demand; this amount is then the share ascribed to answer = yes. The share of demand, which is not met by European production, can be assumed to be produced abroad for export to the EU in a region representing the marginal supplier of the desired crop.

Question 2 Regarding question 2 in Fig. 1, it is hard to determine a proper way to allocate shares to yes and no. There is little help in using market information. If the land available for agriculture is constrained, as in the EU, the causes of increased production have to be established as a share relating to increased yield and a share relating to displacement of other crops. Alter-

[0] Price elasticity on demand is defined as: the relative change in demand divided by the relative change in price, and price elasticity on supply is defined as: the relative change in supply divided by the relative change in price (Madsen et al. 1988)

natively, allocation between yes and no in question 2 may be determined by the aim and scope of the LCA. As a default the answer could be yes in regions with constrained land (displacement of other crops) and no in regions where agricultural land is flexible (increase of production).

Questions 6 and 9 Increased demand for a crop may only partially be met by a corresponding net increase in supply. As mentioned, price elasticities may not help answering questions 6 and 9 in Fig. 1. Therefore, more generalised measures can be applied. Such general measures could be taken from scenarios from agricultural outlook, e.g. FAO (2003a), where scenario modelling shows that decreased production in the OECD countries only leads to an increased production of 23% for maize and 30% for wheat in developing countries. However, applying this would imply that demand is not equal to supply. Such assumptions are not common in LCA and, therefore, it is not recommended to apply such inequalities. Hence, the default answer to questions 6 and 9 is yes.

3 Application of the methodology—illustrative case study

To facilitate the application of the proposed method and to monitor the effect of different scenarios for how increased demand for agricultural products can be met, this section presents an illustrative empirical study on increased demand for wheat in Denmark. The goal of the empirical study is to assess the environmental impact from different ways of meeting increased demand for wheat in Denmark. Of particular interest is the effect of different routes through Fig. 1 compared to attributional LCA. The functional unit is defined as 1 kg wheat demanded in Denmark. The LCA screening is performed by use of the pc software SimaPro 7.0. Wheat is chosen as a case because it is a relatively simple commodity with no co-products that would make this illustrative case study unnecessarily complex. For simplification reasons it is assumed that the by-product straw does not displace anything (the same as 100% allocation to crop in attributional LCA).

3.1 Scenarios

The scenarios are defined correspondingly to Fig. 1. Scenarios 1 and 2 represent the two extreme ways in which system 1 can be affected; i.e. wheat production is augmented in Denmark either by increased area or increased yield. Scenario 3 represents a situation in which system 2 is affected; i.e. wheat in Denmark displaces another crop, which is compensated for by increased production abroad. Scenarios 4 and 5 represent the two extreme ways in which system 4 can be affected; i.e. increased demand for wheat in Denmark is met by increased import produced either by increased area abroad or increased yield abroad. Scenarios 1 to 5 represent situations in which only one system in Fig. 1 is affected. Therefore, scenario 6 considers more than one system as affected.

Besides scenarios 1 to 6, an additional scenario representing the attributional way of defining system boundaries in agricultural LCA has been included. For each scenario, the system affected relating to Fig. 1 is specified in brackets. The features of the scenarios are summarised in Table 2. Not all scenarios are realistic

Table 2 Route map directions through Fig. 1 for the included scenarios

Question	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
1	Yes	Yes	Yes	No	No	Yes=40%, no=60%
2	No	No	Yes	–	–	No
3	t=100%	s=100%	–	–	–	s=100%
4	–	–	Barley: 0.72 kg	–	–	
5	–	–	Canada	–	–	
6	–	–	Yes	–	–	
7	–	–	t=69%, s=31%	–	–	
8	–	–	–	EU	EU	EU
9	–	–	–	Yes	Yes	Yes
10	–	–	–	t=100%	s=100%	t=9%, s=91%
Affected system	System 1	System 1	System 2	System 4	System 4	System 1 and 4

Scenario 7, which represents the attributional way of conducting agricultural LCAs, is not covered by the framework presented in Fig. 1. The bottom line specifies the affected systems in Fig. 1

suggestions on how increased demand will be met. The extreme scenarios are especially regarded as unrealistic. The combined scenarios (scenario 3 and 6) represent the most realistic scenarios.

However, this article does not aim at pointing out the most likely route through Fig. 1. This is because the answers to the ten questions in Fig. 1 are highly dependant on how the market will develop in the future. Examples of important parameters in this respect are: How will the demand for biofuels develop? To which extent will set-aside areas be taken into cultivation? To which extent will policy makers allow inclusion of nature for increased cultivation for biofuel purposes? And to which extent will policy makers allow burning of food commodities for biofuel purposes? These issues are considered out of scope for this article.

Scenario 1 *Increase by area in Denmark (system 1)*. This scenario represents the situation in which the increased demand for wheat is met by expanding the net cultivated area in Denmark. The probability of this scenario may be questioned, but the inclusion of a greater share of set-aside areas in agricultural production in the EU is an option discussed in the debate of cultivation of biofuels.

Scenario 2 *Increase by yield in Denmark (system 1)*. Scenario 2 represents the situation in which the increased demand for wheat is met by increased yield in Denmark. As the agricultural area in the EU has been slightly reduced during the last decades, it may be argued that it is not likely to increase in the future. Therefore, if no other crops should be affected, increased production in the EU is most likely to take place by raising the yield. However, it must be stressed that as fertiliser application in the EU is relatively high, current regulation prevents additional fertiliser application in some areas. Thus, this scenario is realistic only for some regions/farms or if the regulation of fertiliser input is changed.

Scenario 3 *Increase at the expense of other crops (system 2)*. The affected system in this scenario is system 2 in Fig. 1. The increased demand for wheat in Denmark is assumed to be met by an increased Danish production that takes place at the expense of the marginal crop in Denmark. Weidema (2003) identifies barley or wheat as the marginal crops in the EU. According to FAPRI (2006a), Canada is predicted to face the largest gross increase in production of barley during 2005/06 to 2015/16. Thus, Canada is assumed to be the marginal suppliers of barley and hence, Canada is expected to increase its production of barley to compensate for decreased production in Denmark. Distribution between increase in area and yield in Canada is calculated based on predictions for 2005/06 to 2015/16 in FAPRI (2006a). The predicted annual average increase in production of barley in Canada from 2005/06 to 2015/16 is 1.8%. This increase is distributed on average annual increases in area and yield of 1.2% and 0.6%, respectively; thus t=69% and s=31%.

The wheat and barley yields in Denmark are 7,200 and 5,200 kg/ha, respectively (FAOSTAT 2006). The yields are given as five year averages from 2001 to 2005. The average barley yield in Canada from 2001 to 2005 is 2,800 kg/ha (FAOSTAT 2006). Thus, the production of 1 kg wheat in Denmark is likely to displace 0.72 kg barley produced in Denmark (5,200 kg/ha divided by 7,200 kg/ha). Subsequently, this scenario this will lead to increased production of 0.72 kg barley in Canada. The transformation of nature in Canada can be determined as t=69% of 0.72 kg barley. With a yield of 2,800 kg/ha, this corresponds to 1.8 m^2. The modelling of increased yield of barley in Canada is described in Section 3.2.

Scenario 4 *Increase by import from EU, increase by area (system 4)*. This scenario represents the situation in which the increased demand for wheat in Denmark is met by increased import. According to FAPRI (2006a), the EU is predicted to face the largest gross increase in production of wheat during 2005/06 to 2015/16. Thus, the EU is assumed to be the marginal suppliers of wheat. Increased production in the EU is met by increased cultivated area in this scenario.

Scenario 5 *Increase by import from EU, increase by yield (system 4)*. In this scenario, the increased demand for wheat is met by increased import from the EU as in scenario 4. However, in this scenario increased production is met by increased yield.

Scenario 6 *Increase in DK and the EU (price elasticities) (system 1 and 4)*. In this scenario, it is assumed that part of an increase in demand for wheat in Denmark can be met by increased production in Denmark. The response of Denmark's agriculture due to increased demand for wheat is estimated by using price elasticities on demand (η_D=−0.30) and supply (η_S=0.12) (FAPRI 2006b). The price elasticities given in FAPRI (2006b) applies to the EU. It is assumed that they apply to Denmark in this

scenario. By applying formula 1, the increased production in Denmark as a consequence of increased demand of 1 kg wheat can be determined as 0.4 kg. Since, the total agricultural area in Denmark has been slightly decreasing from 1994 to 2004 and, during the same period, the wheat area harvested has been almost constant, it is assumed, that the increased wheat production in Denmark is met by increased yield, i.e. s=100%. The remaining 0.6 kg is imported from the rest of the EU. Distribution between increase in area and yield in the EU is calculated based on predictions for 2005/06 to 2015/16 in FAPRI (2006a). The predicted annual average increase in production of wheat in the EU from 2005/06 to 2015/16 is 0.67%. This increase is distributed on average annual increases in area and yield of 0.06% and 0.6%, respectively; thus t=9% and s=91%.

Scenario for attributional LCA This scenario represents the attributional way of defining system boundaries in LCAs of agricultural products, i.e. no system expansion in the agricultural stage. The inventoried system simply determines the interventions from the cultivated area disregarding any effects on other crops or yields.

The relation between the six scenarios and questions 1 to 10 in Fig. 1 is summarised in Table 2.

3.2 Data collection, inventory data

The life cycle inventory of wheat and barley production in Denmark is based on the Danish LCAfood database, which is available in SimaPro 7.0 (Nielsen et al. 2005). The inventory data for wheat production in the EU and barley production in Canada also take their point of departure in LCAfood and are adjusted to fit agricultural practice in these regions. The inventory data and adjustments of the data in LCAfood for normal cultivation (with present yields) as well as the cultivation with increased yield are described in the following.

3.2.1 Normal cultivation

To standardise data for Denmark, the EU and Canada, the following parameters in the data from LCAfood are adjusted: yield (based on FAOSTAT 2006), fertiliser application per ha (based on Plantedirektoratet 2005 for Danish agriculture and IFA et al. 2002 for agriculture in the EU and Canada) and emissions related to the N and P cycles, i.e. ammonia, dinitrogen oxide, nitrate and phosphate. N- and P-related emissions are determined by use of a balance approach. The balance is established by the inputs: N content in seed, N from deposition, N from fertiliser application and the outputs: N in harvested crop and N in straw removed from the field. Changes in soil matter N have been omitted due to great site-specific variations (soil type and history), interactions with other production systems (manure), uncertainties in modelling, and lack of data from outside Denmark.

On the input side of the N balance, N content in seeds and straw is based on Møller et al. (2000). N deposition in Denmark is on average 15 kg N/ha (Ellermann et al. 2005). N deposition in EU and Canada is estimated based on Bergström and Jansson (2006), where the N deposition in 21 spots in the EU and 21 spots in the US is given. Data for the US are assumed to be representative for Canada. The N deposition is applied as the average of the 21 spots in the EU and the 21 spots in the US. Thus, N deposition in the EU is 6.6 kg N/ha and in Canada 3.3 kg N/ha. The fertiliser application for wheat in Denmark is 161 kg N/ha, 22 kg P/ha and 70 kg K/ha (Plantedirektoratet 2005). For barley in Denmark, the values are 121 kg N/ha, 23 kg P/ha and 55 kg K/ha (Plantedirektoratet 2005). The average fertiliser application for wheat in the EU is 125 kg N/ha, 46 kg P_2O_5/ha and 40 kg K_2O/ha (IFA et al. 2002). In Canada the fertiliser application for barley is 67 kg N/ha, 26 kg P_2O_5/ha and 10 kg K_2O/ha (IFA et al. 2002).

On the output side of the N balance, N in harvested crop and straw is based on Møller et al. (2000) and yields. Straw left in the field in Denmark is 54% (Danmarks Statistik 2006). The share left in the field in Canada and the EU is assumed to be 75%.

The distribution of the N surplus from the balance on ammonia, dinitrogen oxide, and nitrate is determined in the following way: First, the ammonia emission from crop and fertiliser is determined by applying a default share of applied fertiliser N that volatises as ammonia (2% of applied N) and a default value of ammonia emission from crops based on Andersen et al. (2001): 5 kg N/ha for crops in Denmark and the EU (intensive agriculture/high fertiliser input) and 3 kg/ha for crops in Canada (extensive agriculture/low input of fertiliser). It is stressed that these values are attended with some uncertainty due to the lack of knowledge of ammonia emission from crops (Andersen et al. 2001).

Second, the total denitrification is calculated by using a model presented in Vinther and Hansen (2004). Calculation of the dinitrogen oxide part of the total denitrification is very dependant on the model used. Therefore, three different models have been used: IPCC (2000), Vinther and Hansen (2004) and FAO and IFA (2001). In general the models show good coherence, i.e. the calculated N_2O emission varies with a factor 1.1 to 1.3 for cultivation in DK, EU and Canada. The used value is expressed as the

average value of the three models. The nitrate emission is then regarded as the residual. A detailed description of the method applied for establishing the N and P balances is given in Schmidt (2007).

The inventions related to traction per hectare cultivated crop in LCAfood are applied to Danish agriculture as well as agriculture in the EU and Canada. As traction in LCAfood accounts only for ~10% of the total contribution to the impact category of global warming, the uncertainty related to this assumption is assessed as being less significant. The LCA does not ascribe credits to utilisation of straw, husk, germ and bran. Thus, no co-products from wheat production are considered.

3.2.2 Cultivation with increased yield

The modelling of wheat and barley production by increased yields takes its point of departure in present yields in Denmark 7.2 t/ha for wheat and 5.2 t/ha for barley, the EU 5.4 t/ha for wheat and Canada 2.8 t/ha for barley (FAOSTAT 2006). Present yields are adopted as averages from 2001 to 2005. Annual predicted yield increases during 2005/06 to 2015/16 are 31.3 kg/ha for wheat in the EU, 31.2 kg/ha for barley in the EU and 17.6 kg/ha for barley in Canada (based on FAPRI 2006a). The predicted yield increases in the EU, given in FAPRI, are assumed also to represent yield increases in Denmark. The affected interventions when modelling production as increased yield are those which are related to the N cycle due to changes in input of N fertiliser (no changes in traction and application of P and K fertilisers are assumed). Thus, modelling of wheat and barley by increased yield can be determined as:

- 1 kg wheat in Denmark: 319 m^2y (yield 7,231 kg/ha) minus 319 m^2y (yield 7,200 kg/ha)
- 1 kg wheat in the EU: 319 m^2y (yield 5,431 kg/ha) minus 319 m^2y (yield 5,400 kg/ha)
- 1 kg barley in Denmark: 321 m^2y (yield 5,231 kg/ha) minus 321 m^2y (yield 5,200 kg/ha)
- 1 kg barley in Canada: 568 m^2y (yield 2,818 kg/ha) minus 568 m^2y (yield 2,800 kg/ha)

The areas that support a yield increase of 1 kg crop given above are determined from the predicted annual yield increases. The additional fertiliser application needed to have 1 kg increased yield on the areas given above is estimated from Table 1.

In Table 1, it is chosen to apply data for Δyield/ΔN rate for Sweden, as these data are assumed to best fit the regions and crops affected. The fertiliser application for wheat and barley in Denmark falls within the intervals 150–200 kg N/ha and 100–150 kg N/ha, respectively. The fertiliser application for wheat in the EU falls within the interval 100–150 kg N/ha and fertiliser application for barley in Canada falls within the interval 50–100 kg N/ha. Applying the data from Table 1, it can be calculated that to meet the yields presented in above bullets, an additional 7.8 kg N/ha is required for wheat and barley in Denmark, an additional 2.6 kg N/ha for wheat in the EU and an additional 1.0 kg N/ha for barley in Canada. It is stressed that additional fertiliser input in Denmark is not possible in most regions because maximum limits of N input have nearly or already been reached.

3.2.3 Nature

When nature is transformed into agriculture, the emissions from the transformed nature are avoided. These interventions only include emissions related to the N cycle where the only input is deposited N from air. The N balance for nature has been established by using the same method as for agricultural soils. However, the models used for calculating dinitrogen oxide emissions from crops are not applicable to nature. Therefore, a value for direct N_2O emission of 0.46 kg N_2O/ha representing measures from set-aside areas in Germany has been applied (Ruser et al. 2001). The N_2 part of denitrification from nature is estimated from the 0.46 kg N_2O/ha using an average N_2–N/N_2O–N ratio at 3.9 for average soils (Vinther and Hansen 2004). Furthermore, the values for ammonia emission from crops at 3 kg/ha for extensive agriculture is not applicable for EU and Canada as denitrification and ammonia would exceed the input from deposition. Hence, the balance is established for nature in Denmark and balances for EU and Canada are carried out by scaling all inputs and outputs relative to the input (N deposition).

Table 3 summarises the direct interventions from the agricultural stage in the different possible affected subsystems in Fig. 1. The remaining inventory data, which are not shown in Table 3, are documented in Nielsen et al. (2005).

3.3 Life cycle impact assessment— comparison of scenarios

The inventory is compiled into three impact categories: global warming, eutrophication and land use. The EDIP97 method is used for global warming and eutrophication (Wenzel et al. 1997) and land use is measured as occupied area multiplied with the duration of occupation. The comparison of the seven scenarios is shown in Fig. 2.

It appears from Fig. 2 that the contributions to the included impact categories vary significantly among the different scenarios. Regarding global warming, the contributions vary by up to a factor of nine; for eutrophication, variations are up to a factor of 43, and for land use the contribution varies from zero to 1.85 m^2y per kilogram

Table 3 Direct emissions related to the N and P cycles in the different possible subsystems affected

Subsystem	kg NH_3/ha to air	kg N_2O/ha to air	kg NO_3^-/ha to water	kg P/ha to water
Wheat				
DK: 1 ha wheat, normal cultivation	10.0	4.3	159	0.06
DK: 1 ha wheat, increased yield	10.2	4.5	189	0.06
EU: 1 ha wheat, normal cultivation	9.1	3.7	120	0.17
EU: 1 ha wheat, increased yield	9.2	3.7	129	0.17
Barley				
DK: 1 ha barley, normal cultivation	9.0	3.7	157	0.21
DK: 1 ha barley, increased yield	9.2	3.9	186	0.20
Canada: 1 ha barley, normal cultivation	5.3	2.6	70	0.10
Canada: 1 ha barley, increased yield	5.3	2.6	73	0.08
Nature				
DK: 1 ha nature	3.6	0.5	47	0
EU: 1 ha nature	1.6	0.2	21	0
Canada: 1 ha nature	0.8	0.1	10	0

wheat demanded in Denmark. It also appears that the contributions to global warming and eutrophication to some extent are inversely proportional to contributions to land use (see scenarios 1, 2, 4 and 5; the other scenarios are mixtures of affected systems). In general, this means that intensification causes increased global warming and eutrophication but has little effect on land use. On the other hand, extensification increases land occupation, while its contribution to global warming and eutrophication is less significant. It is also important to note that Fig. 2 shows a smaller environmental impact when increasing yields in the EU (scenario 5) than increasing yields in Denmark (scenario 2). Thus, it is most environmentally profitable to increase yields in the region with lowest fertiliser input, i.e. the EU. On the other hand, it is relatively more environmentally profitable to raise production by increasing the area in Denmark (scenario 1) than in the EU (scenario 4). This means that the contribution to global warming is only a factor of 1.1 higher in Denmark than in the EU, while the contribution to land use is a factor 1.3 lower in Denmark than in the EU.

However, it should be stressed that in the above-derived ranking of extensification and intensification, only the effects on global warming, eutrophication and land use have been considered. There are probably important potential impacts related to the use of pesticides in intensive

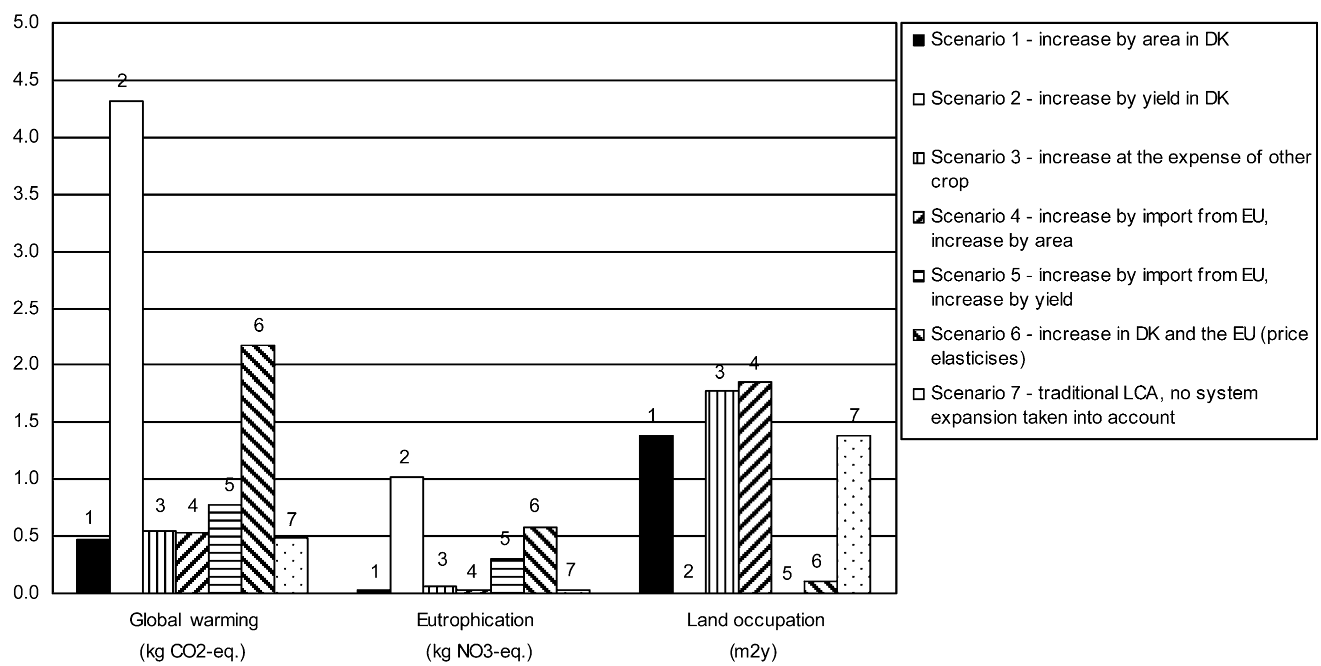

Fig. 2 Comparison of scenarios. The results are shown as characterised results and are related to the functional unit: 1 kg wheat demanded in the EU

cultivation, which are not incorporated in this study. Also, the results for increased yields are based on data in Table 1, which are divided into very coarse intervals. Thus, the difference between additional fertiliser needed per kilogram of increased yield in Denmark and the EU may be overestimated.

4 Discussion

The comparison of scenarios showed significant differences in contribution to the included impact categories. Therefore, the modelling of how increased demand is met in an LCA is crucial for the outcome. Often in LCA, a local simplified and incomplete route through Fig. 1 is taken for granted, assuming local production and the hypothesis that this change has no effect on any part of the rest of the global agricultural system. Some LCAs include substituted agricultural products from co-products. Examples are Nielsen et al. (2005), Dalgaard et al. (2008), Cederberg and Stadig (2003) and SenterNovem (2005). So far, however, it has not been possible to identify any agricultural LCAs that include the actual affected suppliers in terms of interactions between crops and distribution between increased area and yield. In this respect, two questions have to be answered: 1) do the results of LCAs using marginal technology and system expansion reflect a more correct picture of the actual potential environmental impacts than attributional LCAs using average technology and allocation factors in co-producing processes? and 2) what are the potential consequences for decision-making relating to agricultural products applying the consequential vs the attributional approach?

The first question regarding consequential vs attributional LCA has been debated in several publications, e.g. Weidema (2003) and Guinée et al. (2002). The general critique of applying average technology as often done in attributional LCAs is based on the fact that the included processes do not reflect the actual affected processes. As argued in the empirical study on wheat, it is more likely that the most significant processes are those that are not related to the locally cultivated fields with the crop of interest—and in attributional LCAs, the only included processes are these. In this case, the consequential approach reflects the actual affected processes and the accompanying potential environmental impacts in a more realistic way. However, if the aim of the LCA is to allocate a society's total environmental impact on the activities, products and services used in that society, the attributional approach would be relevant.

However, it may be questioned whether such LCAs can be adequately used for decision support. In the case of agricultural products, an attributional LCA would not capture how production is increased and which secondary effects this would have on other crops in areas where the agricultural area is constrained. Thus, an attributional LCA may only cover a part of the actual potential impacts. This part may, according to Fig. 2, in some cases be relatively small. Even though the consequential approach can be argued as the one that best describes the actual affected processes, the identification of marginal suppliers and the prediction of how production is increased (area or yield) are often attended with considerable uncertainties. Keeping that in mind, it is hard to say which of the approaches will end up with a result closest to the actual potential environmental impacts.

The second question is related to the consequences for decision-making and the approach to system delimitation. As a consequence of the above-mentioned blind spots in attributional LCAs on agricultural products, it may be argued that these often cannot provide decision-makers with sufficient information. This may be a problem because the environmental information given to decision-makers has blind spots, which may hide significant direct effects, such as increased yields with significantly higher contributions to global warming and eutrophication than those predicted in the LCA; or secondary effects such as increased demand for import of displaced local production, which may cause transformation of nature into agricultural land in regions that are rich in biodiversity. Still, the consequential approach introduces some additional uncertainties: identification of marginal crops and suppliers, predicting how production is increased (area or yield) and modelling of emissions when increasing yield. Therefore, the important task is to assess whether attributional relatively robust LCAs with inherent unknown blind spots or consequential, relatively uncertain but complete LCAs should be used as decision support. In any case, it should be ensured that undesirable decisions based on wrong assumptions about blind spots in attributional LCAs are avoided.

5 Conclusions

This article argues that the attributional way of defining system boundaries in agricultural LCA implies several blind spots. These include the lack of general considerations on how increased production is achieved to meet the demand of interest (increased area or yield), and the deficient consideration of secondary effects on cultivation of other crops or social/hunger effects.

The proposed methodological framework for capturing these blind spots points at four possible systems to be affected as a consequence of increased demand for an agricultural crop, see Fig. 1. The new aspects that are

possibly affected compared to attributional LCAs are: 1) when demand for a crop in a region increases it may in the end be met by one or a combination of increased yields, increased cultivated area or increased food insecurity in other regions; 2) the increased production of a crop in a certain region may be carried out in practice by the displacement of other crops in the region; and 3) when increasing the cultivated area, emissions from non-cultivated nature are avoided.

Aside from identifying typical blind spots in attributional system delimitation in agricultural LCA, this article also presents some guidance in modelling consequential system delimitation. This includes guidance on how to identify marginal suppliers, how to allocate between increased area and yield when cultivation is increased in a certain region; how to model emissions from increased yield; and how to use price elasticities for estimating the response of local production as well as foreign production to a specified increase in demand. This enables the LCA practitioner to identify possible scenarios of how increased demand can be met.

6 Recommendations and perspectives

The empirical study of environmental impacts related to increased demand for wheat in the EU showed significant differences in the results depending on the way in which the demand is met. Six of the seven scenarios reflect alternative ways of meeting increased demand for wheat by applying the proposed framework, while the seventh scenario represents the attributional way of defining system boundaries in the agricultural stage of LCA. The six so-called consequential scenarios conform to common cultivation rules such as: it is more environmentally efficient to increase yields in extensively cultivated areas than intensively cultivated areas; and intensification causes increased emissions but has no effect on land use, while extensification causes less emissions but requires more land.

From the discussion, it appeared that the methodology proposed in this article contributes to an increased completeness of identifying the actually affected processes. At the same time, it also adds additional uncertainties. These uncertainties are in particular related to the identification of marginal crops and suppliers, prediction of how production is increased (area or yield) and modelling of emissions when increasing yields. On the other hand, attributional LCAs of agricultural products only deal with the emissions that are directly connected to the present production of the crop of interest. This implies that the blind spots described above are not considered. Thus, when conducting agricultural LCAs for decision support there should be a weighting between a consequential, more complete but less certain LCA and an attributional and more certain LCA, though with inherent blind spots.

No matter which approach is chosen, attention must be drawn to the fact that the lack of focus on blind spots may lead to undesirable decisions. If a full quantification of the methodology presented in this article is assessed as being inappropriate, it is recommended to describe the most likely routes through Fig. 1 in a qualitative way. This approach facilitates the making of reservations to the conclusions drawn on the basis of an attributional LCA.

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